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Centrifuge modelling of fibre-reinforcement using as a liquefaction countermeasure of quay wall backfill

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ABSTRACT

Two centrifuge tests were carried out to evaluate the use of fibre-reinforcement to mitigate backfill liquefaction induced damage behind a caisson type quay wall. Liquefiable clean sand backfill was applied in one test as a benchmark of the other in which the whole backfill was fibre-reinforced. The presence of fibres in backfill effectively reduced lateral displacement of quay wall and backfill settlement. Quay wall outward displacement induced an excess pore pressure drop in the clean sand backfill adjacent to the back of quay wall, while this phenomenon did not occur in fibre-reinforced backfill. Increase of shear strength and self-supporting behaviour at large shear strain may be the beneficial effects of fibre-reinforcement.

Introduction

Severe damage of caisson type quay walls have been caused by backfill liquefaction during earthquakes in recent decades, such as cases in Kobe earthquake, Japan, 1995, Kocaeli earthquake, Turkey, 1999, and Chichi earthquake, Taiwan, 1999 (Inagaki et al. 1996, Sumer et al. 2002, Lee 2005). To reduce such risk to similar waterfront retaining structures in seismically active areas, finding an effective method to improve liquefaction resistance of backfill is necessary.

Fibre-reinforcement technique has attracted attentions of geotechnical engineers since early 1980s as it can eliminate the occurrence of a weak plane of soil and does not require new mixing procedures (Tang et al. 2007). Drained element tests, including direct tests and compression triaxial tests (Gray and Ohashi 1983, Gray and Al-Refeai 1986, Al-Refeai 1991, Consoli et al. 2007), have generally demonstrated effects of fibres on improvement of the peak strength and reduction of post-peak strength loss of composites. Undrained tests (Ibraim et al. 2010, Liu et al. 2011) have shown that fibres can potentially prevent of static liquefaction and lateral spreading. Influences of fibres on soil liquefaction under seismic loadings were investigated by Krishnaswamy and Thomas Isaac (1994), Boominathan and Hari (2002). They concluded that saturated fibre-reinforced soil requires many more loading cycles to initiate liquefaction. Maheshwari et al. (2012) pointed out that the maximum excess pore pressure and ground surface settlement of fibre-reinforced soil were less than unreinforced ones through a series of small shaking table tests. Outcome from centrifuge tests (Wang and Brennan 2014) suggest that large strain potential is required to mobilize the effectiveness of fibre-reinforcement to mitigate liquefaction induced hazards.

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Two centrifuge tests were conducted to evaluate fibre-reinforcement technique as a countermeasure against backfill liquefaction behind caisson type quay wall in this study (layouts are schematically shown in Figure 1). Effects of fibres on the lateral displacement of quay wall, backfill settlement and excess pore pressure within the backfill adjacent to the back of quay wall are shown by relevant measurements and mechanism of fibre benefits are discussed.

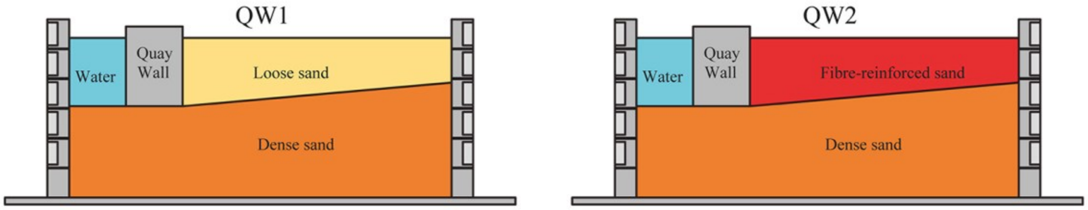

Figure 1 Centrifuge test layouts

Centrifuge Modelling

Centrifuge tests in this study were carried out on the centrifuge at University of Dundee with the newly installed 1-D servo hydraulic earthquake simulator. Details of these facilities are provided in Brennan et al. (2014). Although models were prepared in an equivalent shear beam (ESB) box, boundary effects on liquefaction tests are negligible when the measuring place is far enough from side walls (Coelho et al. 2003). Accelerometers (ACCs), pore pressure transducers (PPTs) and linear variable differential transformers (LVDTs) were used for measuring accelerations, pore pressures and displacements respectively. Detailed layout and instruments distribution of QW1 is shown on Figure 2. These were the same in QW2 except backfill material. All dimensions in this figure is in model scale. Both tests were carried out at 50g (i.e. models were at a scale factor of 50). In the section of results of analyses, the scale is in prototype, unless otherwise specified.

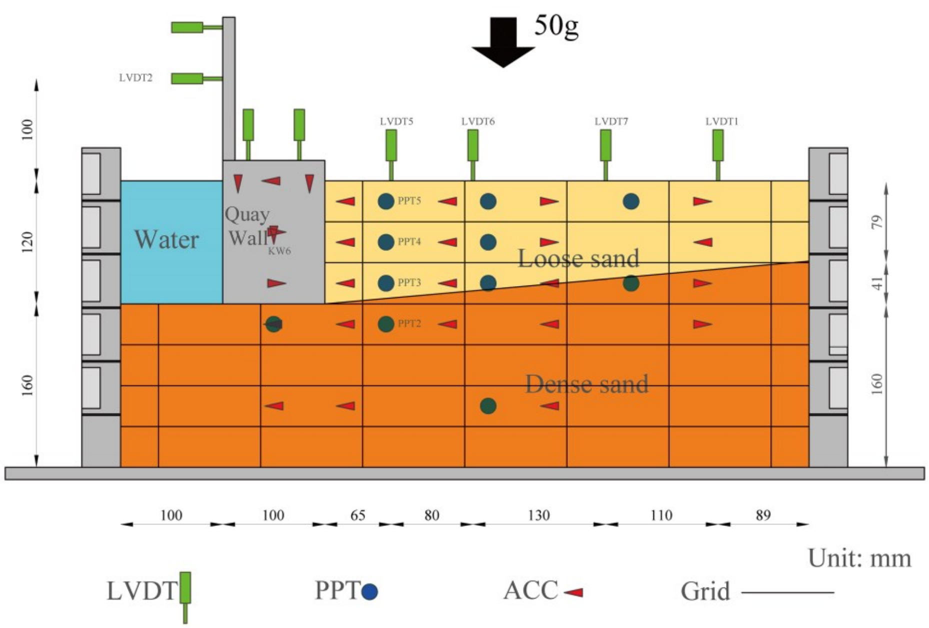

Figure 2 Layout details and instruments distribution

Flexible crimped polypropylene fibres, Loksand™, were used as the reinforcement material. They have nominal length of 35mm, nominal diameter of 0.1mm, specific gravity of 0.91 and tensile strength of 200MPa.

HST 95 Congleton sand was used to build soil foundation and backfill and a small amount of Redhill 100 sand was used to build a marker grid. Properties of both sands are shown in Table 1. Dense soil foundation (D_r = 80%) and loose clean sand backfill (D_r = 40%) were prepared by dry pluviation. Relative density of fibre-reinforced sand was also 40%. The fibre concentration is defined as the proportion of weight of fibres (W_f) to weight of dry sand (W_s): $w_f = W_f/W_s$. Fibre concentration in this study is 0.6%. This fibre concentration of Loksand™ has been applied to provide resistance to deformation of sports pitches, landscaping and grass access roads. Fibre-reinforced sand was also prepared by dry pluviation. Using fibre concentration of 0.6% keep the relative density of the reinforced backfill as 40%, which is consistent with the unreinforced backfill. Further details of the preparation procedures are provided in the work of Wang and Brennan (2014). Note that the fibres and soil particles themselves are not scaled. This is because the soil is treated as a continuum deriving its macroscopic stress-strain properties from the particles/fibres, requiring the same materials to be used in model and prototype. The same rationale of macroscopic behaviour being paramount is used in all numerical modelling, and that reducing the scale of fibres and particles would be both impractical and have questionable macroscopic response.

Table 1 Sand properties.

Sand Type	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	G_s	e_{max}	e_{minn}
HST95 Congleton	0.1	0.12	0.14	2.63	0.714	0.769
Redhill 100	0.08	0.1	0.12	2.65	1.045	0.627

The caisson type quay wall model was constructed using a watertight Acrylic box filled with dry sand for ballast. The average unit weight this model is 17.16kN/m^3. Quay wall model was designed to be stable at 50g but to undergo a sliding failure if excess pore pressure approached liquefaction, in order to achieve a representative lateral spread backfill.

Both tests were conducted under 50g gravitational field, so a methycellulose water solution with 50 times water viscosity was used as the pore fluid. Models were saturated from the bottom and the water level was kept slightly above the surface of backfill.

Two earthquakes were applied consecutively to the base of the model in each test. The input motions consisted of scaled versions of records in Kocaeli earthquake, Turkey, 1999 (fault normal component at Izmit station, NGA1165) and Chichi earthquake, Taiwan, 1999 (fault normal component at CHY014 station, NGA1186).

Results and Analyses

Deformation of Marker Grid

Deformation of marker grid was obtained after each test through excavation (Figure 3). This provides a direct observation of cumulative deformation within backfill. It is clear that clean sand backfill in QW1 severely deformed outward. When away from the quay wall, such deformation tendency reduced. Lateral deformation was negligible in fully fibre-reinforced backfill in QW2. This immediately shows that fibres were effective on reducing the displacement in this system. It is therefore instructive to examine the instrument readings for explanations.

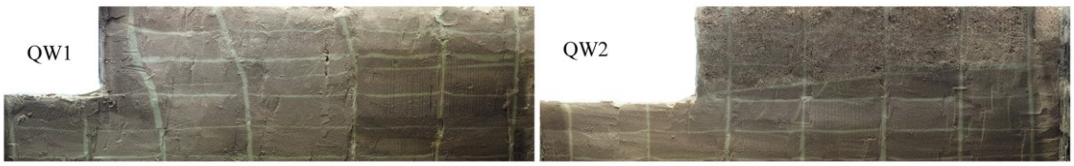

Figure 3 Deformed marker grids

Quay Wall Lateral Displacements

Lateral displacement is the main concern of the quay wall in this study as the tilting and settlement were negligible. This is in accordance with the experiment design. Figure 4 shows time histories of quay wall lateral displacements measured by LVDT2 during and after the two earthquake events. All lateral displacements occurred within the duration of earthquakes. With presence of fibres in QW2, quay wall lateral displacement was significantly reduced. In Kocaeli earthquake event, the displacement in QW2 was almost half of that in QW1. The difference was even larger in Chichi earthquake event. Quay wall in QW1 generally moved in an incremental sliding mode with small displacement steps, while quay wall lurched inward and outward intensively during the general outward movement. Such lurch was more obvious in Chichi earthquake event.

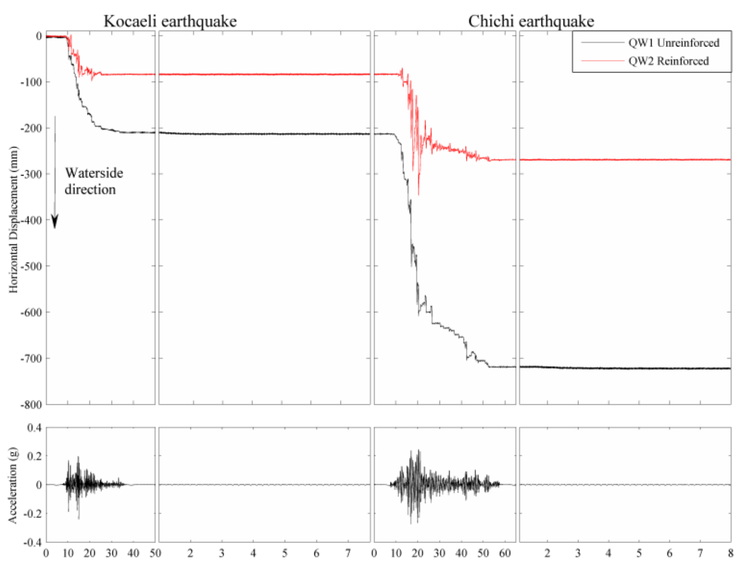

Figure 4 Time histories of quay wall lateral displacement

Backfill Settlement

Figure 5 summarizes LVDT measurements at four positions (3.25m, 7.25m, 13.75m and 19.25m away from the back of quay wall). It is clear that backfill settled unevenly. This is more obvious in QW1. The position adjacent to the backfill (3.25m) suffered most severe settlement while ground settled much less at the position far away from the quay wall. Ground settlement was substantially reduced at all positions with presence of fibres. This is more obvious at the position immediate behind the quay wall. Moreover, post-earthquake settlement was almost prevented in QW2.

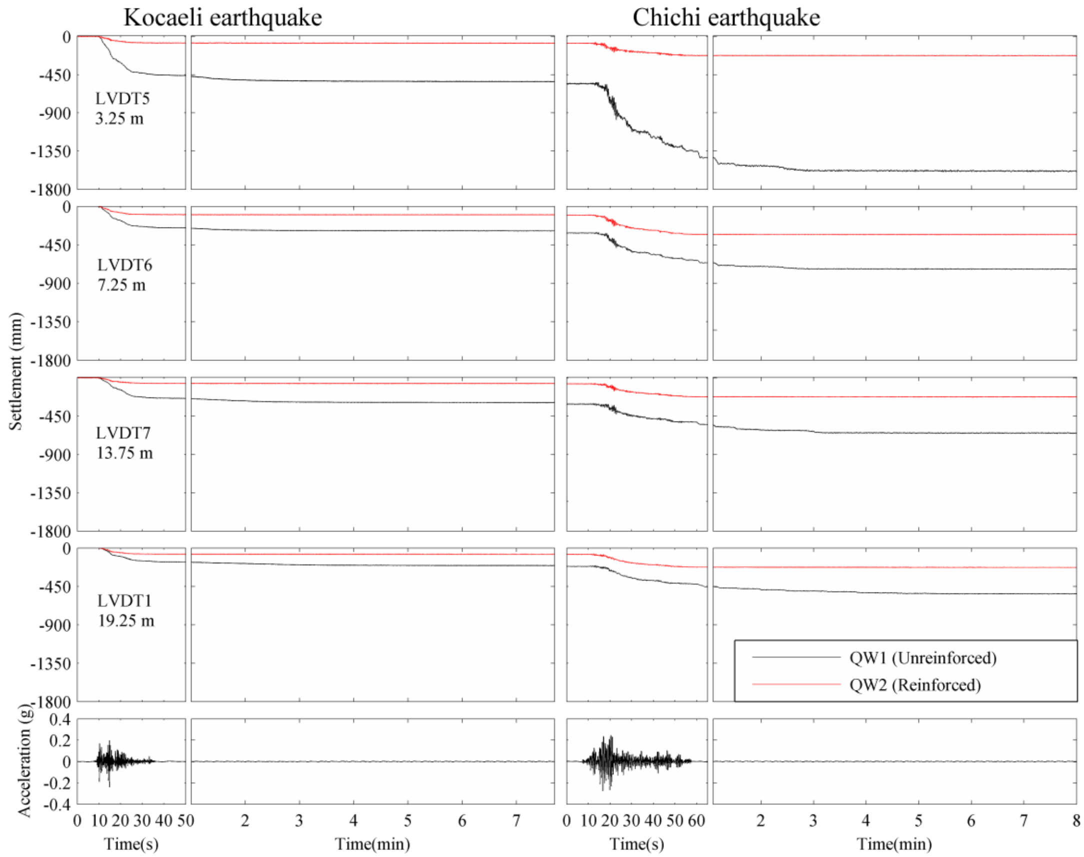

Figure 5 Time histories of backfill settlements

Excess Pore Pressures

The excess pore pressure time histories measured by a vertical PPT array next to the quay wall are shown in Figure 6. The excess pore pressure ratio is defined as $r_u = \Delta u/\sigma'_{v0}$ (where Δu is excess pore pressure and σ'_{v0} is effective vertical stress before the excitation). The value of r_u reaches 1 if the soil liquefies.

The maximum values of r_u in both Koceali and Chichi earthquake events were generally less than 0.8 and even less than 0.6 at depth of 5m, regardless of the presence of fibres. This indicates that liquefaction did not occur in the backfill next to the quay wall in both tests. This is consistent with previous studies and in-situ cases (Ghalandarzadeh 1998, Iai et al. 1998, Lee 2005, Dakoulas and

Gazetas 2008). However, the unreinforced backfill in the first (Kocaeli) earthquake shows a sharp rise followed by a drop in pore pressure. This correlates with expansion of the backfill caused by the large amount of lateral displacement (Figure 4).The reinforced soil shows a slower increase in pore pressure without such drop, relevant to the reduced lateral displacement (Figure 4). In the second earthquake (Chichi) then the reinforced soil shows a similar response but the unreinforced soil has a different pattern of excess pore pressures. This is because the model at the start of this earthquake had already significantly deformed and was no longer the same geometry as either the original model or the comparable reinforced (less deformed) model. Dissipation time histories of excess pore pressure were similar during post-earthquake period in both tests, indicating that fibres had not affected the soil's dissipation characteristics.

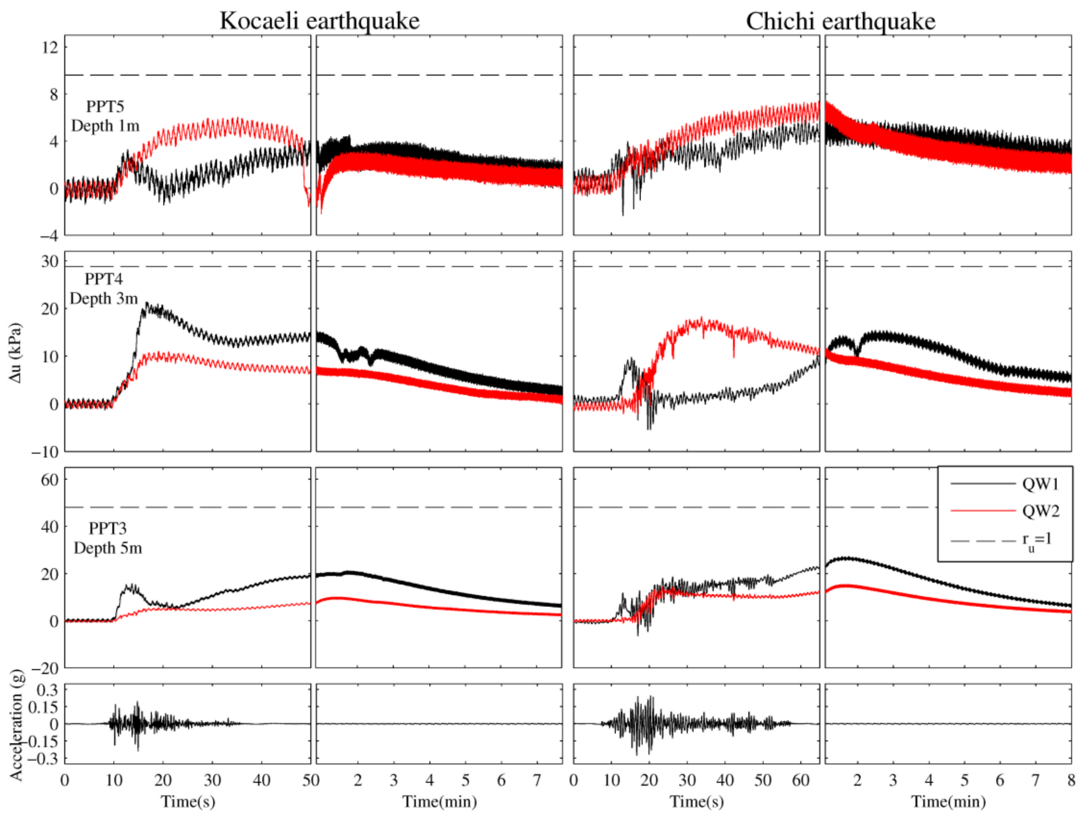

Figure 6 Time histories of excess pore pressures

Discussions

Fibres increase shear strength and reduce stiffness loss of the composite (Liu et al. 2011). These effects are more obvious at large strain when interlocking is fully mobilized between fibres and soil particles (Li and Zornberg 2013). Backfill shear strength increase implies less earth force on the back of quay wall, so less lateral displacement of quay wall is expected with fibre-reinforced backfill. When saturated sand collapses to flow, fibre-reinforced sand still maintains its structure stability (Ibraim et al. 2010). It indicates that backfill may be self-supporting when further quay wall displacement occurs. This may explain the larger difference of quay wall lateral displacement in the second earthquake (Chichi earthquake).

Two causes may induce backfill settlement behind quay wall during earthquake: outward movement of quay wall and consolidation of backfill soil (Lee 2005). As fibres may not apparently affect the soil consolidation during and after liquefaction (Wang and Brennan 2014), limited quay wall lateral displacement by fibres may account for reduction of backfill settlement. This is apparently manifested by the fact that fibres reduced much more settlement in the area adjacent to the quay wall.

Mutual effects between the quay wall displacement and excess pore pressure generation were shown in QW1. Increase of excess pore pressure induces increase of earth pressure, driving quay wall to move outward. The outward movement in turn expands the backfill resulting in a drop in excess pore pressure. The drop of pore pressure again decelerates the quay wall movement. Fibre-reinforced backfill might exert less force on the backfill quay wall when generating excess pore pressure, so the quay wall did not move quickly and far enough to cause a noticeable drop of excess pore pressure.

Fibre-reinforcement has shown a great potential as a countermeasure of liquefaction induced lateral spreading behind quay wall through the two centrifuge tests. Because of the limited number of tests, only fully reinforced case with one fibre concentration was investigated. Further work should include the effects of reinforcement area and fibre concentration on limiting lateral spreading.

Conclusions

Two centrifuge were carried out to evaluate fibre-reinforcement as a countermeasure against damage induced by backfill liquefaction behind caisson-type quay wall. Fibre-reinforcement effectively reduced the outward displacement of quay wall and backfill settlement. Quay wall movement induced excess pore pressure drop in clean sand backfill was eliminated by fibre-reinforcement. Increased shear strength and self-supporting behaviour of fibre-reinforced backfill may be the causes of the benefits.

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